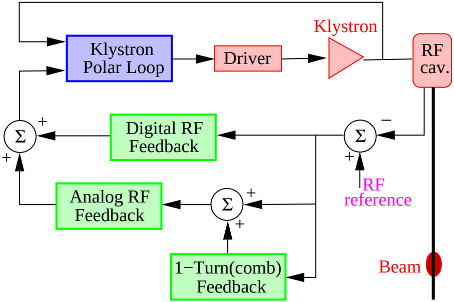
LHC RF Station Configuration Tools and Beam Dynamics-RF Station Interaction Modeling

T. Mastorides[1], C. Rivetta[1], J.D. Fox[1], D. Van Winkle[1], P. Baudrenghien[2], A. Butterworth[2], J. Molendijk[2]

[1] Accelerator Technology Research Department, SLAC

[2] AB-RF Group, CERN

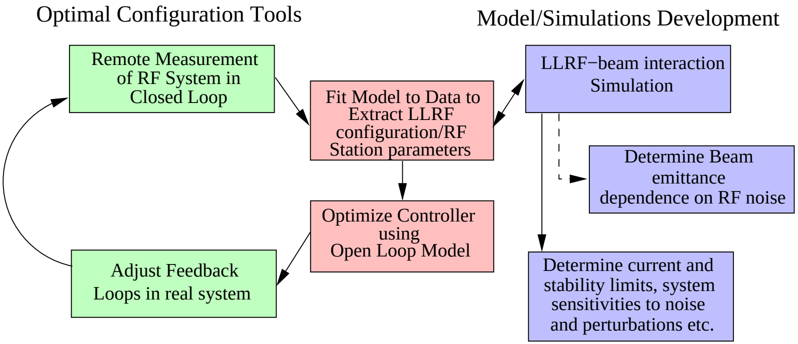
RF Station/Beam Dynamics Interaction



- The longitudinal beam dynamics is mainly defined by the impedance and associated circuitry of RF stations.
- The stable operation requires the control of higher-order mode impedances as well as the precise control of the accelerating fundamental impedance.
- Impedance controlled LLRF architectures modify the impedance seen by the beam with feedback techniques. This system has multiple dynamic loops. Stability of BOTH the LLRF loops and the beam are necessary conditions.

LHC LLRF Effort

Work to date fits into two **related** activities:



- Open loop transfer function with beam necessary for stability determinations. But, Open Loop is unstable. Fitting tools help us determine the closed loop parameters. We can then use a linear model to find optimal configurations.
- Simulation much more detailed than linear model. Includes non-linearities, details omitted in linear model. Noise injection, dynamic range effects, and digital quantizing effects can and will be added.

1. Introduction
2. **LLRF Commissioning and optimal configuration tools**
3. RF Station/Beam Dynamics Interaction Model
   - Beam Diffusion
4. Conclusions
5. References

Motivation

- In late 2007 the CERN AB-RF group requested LLRF commissioning and optimal configuration tools based on our PEP-II experience
- Consistent configuration of all RF stations to the same operating point
- The stations are initially configured with the tools during commissioning
- In addition, as operating conditions change, it will be necessary to re-configure the RF stations for:
  - Different Cavity Q (injection vs. physics)
  - Detuning
  - Drifts
- Over the last two years SLAC personnel have established a strong collaboration with the CERN AB-RF group, and have successfully developed a suite of tools to align the LLRF in operation, to help in the setting up of the stations after a down time, and to determine deviations between the nominal and measured system behavior (drifts)
- These tools allow remote optimal configuration of the LLRF system. New stricter CERN policies prevent tunnel access when the magnets are energized.

LLRF Alignment Flow

Determining RF-LLRF Parameters

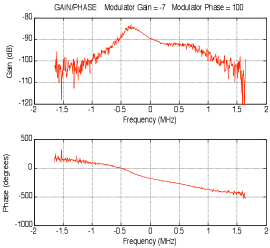
- Transfer function measurements are made using a novel noise injection base band network analyzer
- The transfer function measurements are numerically “fit” to a linear model of the system
- Real system and model include several configurable parameters, which are adjusted for “design” phase and gain margins and applied to the system (variations over stations)

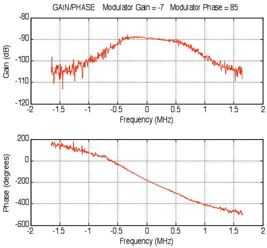
Closed Loop Optimization

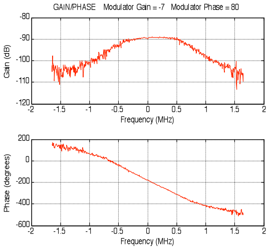
- For the closed loop case, the linear model can be “open looped” to determine the parameter values to achieve the desired phase and gain margins
- The system is re-measured to verify performance.

The Routines

- Nulling
- Digital/Analog Phase Align
- Klystron Bump Nulling
- Open Loop
- Closed Loop
- Klystron Polar Loop







Status

Achievements

- The configuration tools are being currently used at CERN for the commissioning of the RF stations
  - This effort has provided a useful tool which is now being utilized by the CERN AB-RF group - a LARP success
- All open loop routines have been tested and verified
- Closed loop routines are being tested as we speak, in the absence of beam

Future

- Finish testing-debugging of existing routines
- Test with beam? (reluctance due to noise injection)
- Additional functions as more components get commissioned
  - Implement 1-turn feedback
  - Implement Cavity Noise measurement
  - Implement Cavity Q calibration

Interaction Model

- We have a simulation (in simulink) and models for the LHC architecture, parameters, and technical implementation [3]
- We have managed to stay ahead of commissioning, and we hope to continue to do so, with models ready for validation
- From our simulation, we extract beam and station parameters that help us study:
  - Longitudinal beam dynamics
    - Bunch centroid stability, position, and motion
    - Bunch shape and diffusion as a function of the RF and LLRF configurations.
  - RF station
    - Station stability
    - Optimal station configuration
    - How are the operational margins affected by the technical components (non-idealities) and the station configuration?
- Model has been used for the development of the configuration tools

Effect of RF noise on longitudinal beam emittance

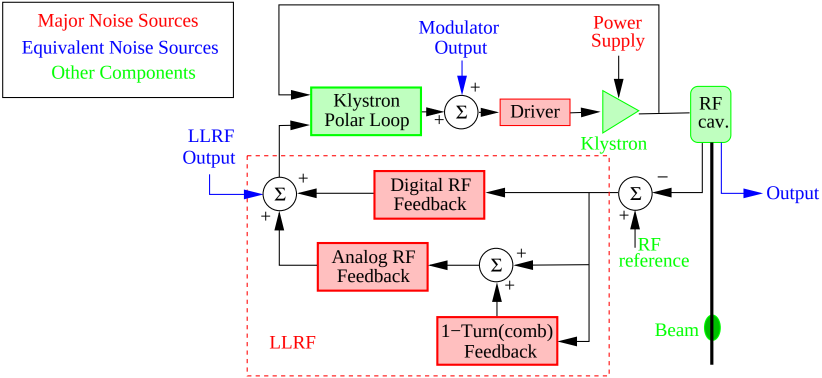
The Equilibrium longitudinal bunch distribution is derived from Fokker-Plank equation:

$$\Psi(r) = \frac{1}{\sqrt{2\pi}\sigma_r} e^{-r^2/2\sigma_r^2}$$

where $\sigma_r^2 = \frac{D}{\alpha}$, α is the rate of energy loss, and D the diffusion coefficient defined by the spectrum of the phase noise in the accelerating voltage

- Beam emittance depends strongly on the accelerating voltage noise spectrum (extremely low synchrotron radiation)
- Study the dependence of the accelerating voltage noise on the various RF parameters and the technical characteristics (such as non-linearities, thermal noise, frequency response etc.) of the LLRF system components

Noise Sources



- We refer the noise of the modulator or the LLRF in two points to analyze their effect on the cavity phase noise. Amplitude noise not significant for beam dynamics.
- The LLRF noise includes several sources (digital quantizing noise and arithmetic noise in digital signal processing, thermal noise).
- Incoherent noise, except from power supplies (50, 100,...600 Hz noise)

What are we studying:

- J. Tuckmantel at CERN has estimated that to preserve the LHC bunch length, the maximum allowed incoherent phase noise from the RF system is 0.5° rms or 3.3 ps at f_{RF} [4].
    - The phase noise for the RF system in the absence of beam has been measured to 24 fs in the band 0-f_{rev} (a margin of 140), **for a particular setting of the LLRF feedback loops**.
- But:
    - noise from the whole band will be aliased over the frequency band from the RF operating frequency out to the first revolution harmonic
    - the various RF configurations will provide different levels of noise rejection.
- Ultimately, we want to determine what technical components dominate, how changes in digital quantizing choices, numeric choices, analog component choices, dynamic range and gain partitioning, noise in HVPS, etc. impact the diffusion coefficient.

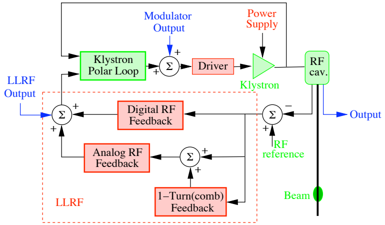
Noise Rejection Measurements

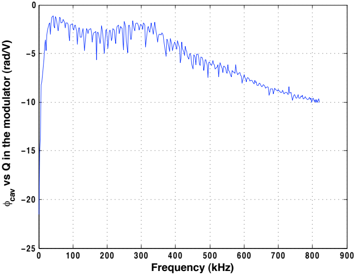
To achieve this:

- We set our simulation to the configurations of interest and measure the transfer function between the noise (I/Q) and the phase of the cavity voltage
- We can then translate the threshold cavity phase noise to an equivalent maximum allowable power spectrum at the output of the modulator or of the LLRF

$$< \phi_{cav}^2 >= \int_{-\infty}^{\infty} |T^2(f)| N(f) df$$

where $N(f)$ is the power spectrum of white noise at the I or Q channel.





Noise Rejection Measurements

Modulator and LLRF noise threshold in $\mu V/\sqrt{Hz}$

Configuration	$V_{Modulator}$		V_{LLRF}		V_{LLRF} $0 - frev$
	I	Q	I	Q	Q
Case1: Begin Injection	314.8	36.3	4555.5	151.5	1681
Case2: End Injection	278.1	36.4	2589.1	151.6	1698
Case3: Physics	877	127	11042	510	5636
Case2 with llrf1	262	364	3736.1	151.3	1683
Case3 with llrf1	568	110	11171	468	3277
Case1 with llrf3	378	29.3	1798.6	120	2861
Case2 with llrf3	361.6	29.2	3697.3	119.6	2863

- Last column corresponds to integration up to f_{rev}. Approximately an order of magnitude difference
- Two orders of magnitude difference between best-worst case scenarios
- Dedicated measurements will be necessary to compare with the real system noise.
- These numbers define the design specifications for the LLRF and Modulator boards
- Insignificant difference with constant 1-turn FB parameters

Further Interaction Model LHC Studies

- Further validation of simulation as operational data becomes available.
- Study "Half-detuning" configurations.
- The f_s crosses 50 Hz during the ramp. J. Tuckmantel has also simulated this effect [5], predicted non-negligible effects, and recommended an alternative ramping scheme with much smaller effects on the beam shape.
  - Determine the sensitivity of the 50 Hz ripple during ramping for all possible RF and LLRF configurations.
- Determine noise contributions from individual elements of the LLRF.
  - Based on the maximum allowed noise, create a "budget" of noise contributions to help with system design.
- Study/determine impact of effective impedance $Z^{eff}(\omega)$ on beam emittance.

Conclusions

Optimal Configuration Tools

- A set of tools has been delivered to the LHC RF group
- It has been used successfully for the RF-LLRF commissioning

RF Station/Beam Interaction Models

- Have been used:
  - in the development of the optimal configuration tools
  - to explore optimal RF/LLRF configurations
  - to estimate beam longitudinal stability for various scenarios
  - to set noise threshold limits for the modulator and the LLRF
- We can study any other possible configuration, proposed design, algorithm, or next generation system
- Results can be helpful for noise allocation and specification of technical components in future designs

Acknowledgments

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- We would also like to thank the SLAC Accelerator Research department for their support and help
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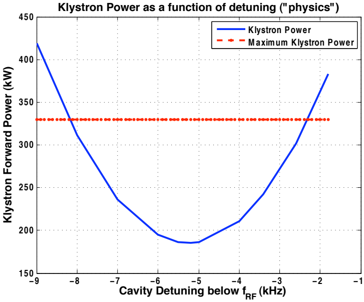
- [2] T. Mastorides *et. al.*, “Analysis of Longitudinal Beam Dynamics Behavior and RF System Operative Limits at High Beam Currents in Storage Rings”, Phys. Rev. ST-AB, 11, 062802 (2008) and SLAC-PUB-13287.
- [3] T. Mastorides *et. al.*, “Modeling and Simulation of the Longitudinal Beam Dynamics - RF Station Interaction in the LHC Rings”, EPAC 2008, Genoa, Italy, June 2008.
- [4] J. Tuckmantel, “Synchrotron Radiation Damping in LHC and Longitudinal Bunch Shape”, LHC Project Report 819, June 2005.
- [5] J. Tuckmantel, “Simulation of LHC Bunches under Influence of 50-Hz multiple Lines on the Cavity Field”, LHC Project Note-404, June 2007.

RF Station Optimal Configurations

Cases Considered:

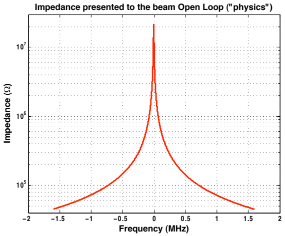
- Case 1) Beginning of injection: $I_o = 0A$, $V_{cav} = 1MV$, $Q = 20k$, cavity detuning $= 0Hz$
- Case 2) End of injection: $I_o = 0.582A$, $V_{cav} = 1MV$, $Q = 20k$, cavity detuning $= 10.5kHz$
- Case 3) Physics: $I_o = 0.582A$, $V_{cav} = 2MV$, $Q = 60k$, cavity detuning $= 5.2kHz$
- Additional cases based on PEP-II operational experience

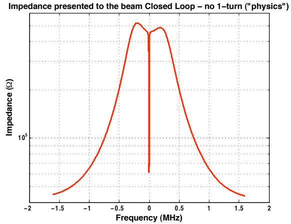
- The LLRF has been set to the values suggested from the RF tools, including changes in the 1-turn feedback.
- Optimal detuning set by minimizing the forward klystron power **for an even fill**.
- “Half-detuning” algorithm will be commissioned in real machine. We are preparing our algorithms and simulation techniques to be ready for this scenario.

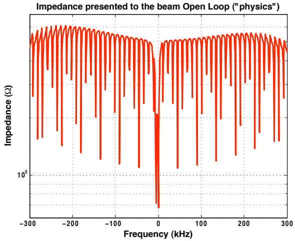


Fundamental Impedance Reduction

- The analog/digital loop and the 1-turn feedback provide a reduction of the superconducting cavity impedance of about 50 dB, as expected.
- We compute the effective cavity impedance using a linear model, based on the system operating points determined from the nonlinear simulation tools.





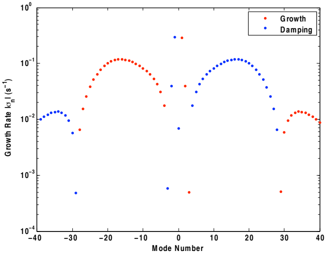


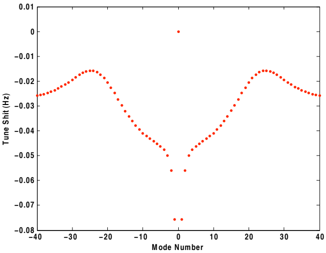
- Impedance shown includes all 8 RF stations.

Modal Growth Rates-Tune Shifts

The Growth Rates can then be computed for various configurations:

With the analog/digital (direct) loop on...





- $\Lambda_n = \lambda_n - d_r + j\omega_s = \left(\mathcal{R}(\lambda_n) - d_r\right) + \left(\mathcal{I}(\lambda_n) + j\omega_s\right) = \sigma_n + j\omega_n$, where $d_r = 13$ hr

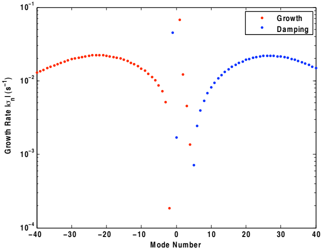
$$\lambda_n = \frac{\alpha q I_0 \omega_{\mathrm{rf}}}{2E_o T_o \omega_s}\left(Z^{\|\mathrm{eff}}(l\omega_0 + \omega_n) - Z^{\|\mathrm{eff}}(0)\right)$$

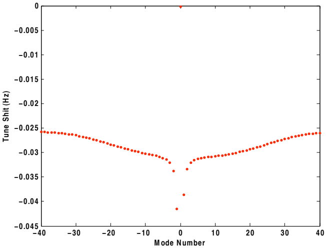
- Fastest growing mode growth rate = $0.288s^{-1}$
- Largest tune shift = $-0.00756Hz$

Modal Growth Rates-Tune Shifts

The Growth Rates can then be computed for:

...the addition of the 1-turn feedback





- Fastest growing mode growth rate = $0.0675 s^{-1}$
- Largest tune shift = $-0.0415 Hz$

Growth Rates-Tune Shifts

Summary of Results/Concerns

Configuration	Fastest Growth Rate (s^{-1})	Highest Tune Shift (Hz)
Case1	0.0611	-0.0084
Case2	0.4683	-0.1152
Case3	0.0675	-0.0415
Case2 llrf1	0.4793	-0.1150
Case3 llrf1	0.0985	-0.0647
Case1 llrf3	0.0855	-0.0107
Case2 llrf3	0.6629	-0.1650

- Growth time in the order of a few seconds.
- Tune shift not significant.
- Insignificant difference with constant 1-turn FB
- More pronounced effect when the RF station is in injection mode, but the LLRF implementation has been set for physics.
- Now, we want to estimate the effect of Landau damping on these growth rates, before we compare them to the synchrotron radiation damping time.
- At this point, growth rates are more of a metric for the effective impedance reduction with various LLRF configurations, rather than the beam dynamics.